Microscopic Description of Giant Dipole Resonances

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The ever-intriguing nuclear many-body system can be better understood by microscopic models, which can relate the microscopic degrees of freedom with the bulk properties that are detectable in the lab setting. Such models become more useful if they can be applied to a large domain of energies, such as temperature extremes (T), spin (I), isospin, and density. Hence, the study of nuclear extremities gains significance, especially in light of recent experimental development. Giant Resonances (GRs) are the fundamental mode of excitations that can be built on any nuclear state and are the most versatile tool to probe nuclei in all possible domains. Most importantly, the microscopic approach to GRs, which connects the single-particle degrees of freedom with the experimental observable collective transitions, can help us better understand the structure of the nucleus itself. GRs manifest as the collective vibration of protons against neutrons under the influence of small external electromagnetic perturbation induced by the absorbed/emitted photons, which leads to a giant peak in the photo-absorption/emission cross-section. Isovector $E1$ (dipole) transition has the highest probability, and thus giant dipole resonance (GDR), which primarily refers to isovector GDR, is the most prominent among all the GRs. The central theme of this thesis work is constructing a more microscopic approach to GDRs, which can be built on various nuclear states and linking them with the underlying nuclear structure.

The theoretical approaches to GDR can be broadly categorized into the macroscopic and microscopic approaches. In the macroscopic model, the GDR is coupled with the shape of the nucleus, hence providing corresponding structure information. On the other hand, the microscopic model describes the GDR as a superposition of particle-hole (ph), particle-particle (pp), and hole-hole (hh) excitations. One of the most prevalent microscopic approaches is the random phase approximation (RPA) based linear response theory (LRT). In LRT, the response of the nucleus to a small external perturbation is calculated using single-particle energies and wavefunctions. We utilize a triaxial Woods-Saxon (WS) Hamiltonian to calculate the single-particle wavevectors and energies. There have been several earlier works that utilized such microscopic models for GDR. Still, most are restricted to only ground state GDR or use more approximate solutions for the single particle wavefunctions. In this work, we utilize a set of triaxial wavevectors obtained from diagonalizing a realistic triaxial WS Hamiltonian on an extensive basis. The same WS Hamiltonian is used to calculate the nucleus's potential energy surface (PES) to obtain the most probable shape. The PES is computed using a Nilsson-Strutinsky method where we calculate the potential energy as the sum of liquid drop energy and the shell correction calculated using the WS Hamiltonian with the correction due to the pairing field obtained using the BCS model. Our results [1] for a recent observation of GDR in $^{144-150}$Nd and ^{152}Sm show that the microscopic approach is more successful and versatile in explaining the experimental data. The equilibrium deformations calculated using our PES are more successful in explaining the experimental cross-sections with both the macroscopic and microscopic models. We highlight the cases where the results from the microscopic approach are sensitive to the change in single-particle configuration despite no change in shape and mass but with a change of two protons in a mid-shell region. We also present the fine structure analysis of

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the GDR cross-section using the continuous wavelet transform (CWT) framework and elucidate the origin of such fine structures.

One of the less explored domains with the microscopic models is the GDR built on a thermally excited system where thermal fluctuations are expected to be large since the nucleus is a tiny finite system. The macroscopic models combined with the thermal shape fluctuation (TSFM) models have successfully explained the experimental data [2]. We extend the microscopic model to the thermally excited system with TSFM, where fluctuations in shape and the pairing field play a significant role in deciding the GDR observables. TSFM considers the thermal fluctuations over various degrees of freedom, such as the shape parameters (β_2,γ), the pairing gap (Δ_P,Δ_N), and so on. This is done using a weighted average of the observable over the considered degrees of freedom, and the weight in the sum is chosen to be the Boltzmann factor [$\exp(-F/T)$]. The free energy F is calculated using the finite temperature Nilsson-Strutinsky (microscopic-macroscopic) approach. In our recent work [3], we present our microscopic model extended to the finite temperature and discuss our results for the nuclei ^{97}Tc, ^{120}Sn, ^{179}Au, and ^{208}Pb and corroborate with the available experimental data. We also compare with the macroscopic model for GDR and show that despite having fewer parameters than the macroscopic model, the microscopic model can reproduce the experimental trend in GDR width in both the Sn and the Pb regions. At very low temperatures, there is a strong interplay between the quantal fluctuations, statistical fluctuations, and residual pairing effects, and our results show that the pairing has an effect of reducing the GDR width at $T < 1$ MeV in both the macroscopic and microscopic results. At higher temperatures ($T > 1.5$MeV), the microscopic model performs poorly as compared to the macroscopic model because it underestimates the experimental width. This is a known behavior of linear response theory based methods where the overall increase in width remains less than 2 MeV for a temperature range of 0 to 2 MeV.

The advantage of using a microscopic description of resonances is that it can be utilized to simulate the response of the nucleus on a quantum computer. Recent advancements in quantum computing enable us to simulate the dynamics of a quantum many-body system such as the atomic nucleus. In our recent work [4], we utilize the Linear Combination of Unitaries (LCU) based algorithm to simulate the Hamiltonian of the system. The response is calculated by obtaining the transition probabilities from the ground state to the excited states using the SWAP test. We offer the possibility of simulating a complete quantum response of the nucleus using already available quantum algorithms and corroborating with the available experimental data for the nuclear response.

We have developed a microscopic approach for GDR, which is extended to thermally excited nuclei. For the first time, we show that the GDR can be sensitive to the underlying single-particle structure of the nucleus. More precise measurements of the fine structure of GDR can help better understand this sensitivity to the single-particle states. As a first-of-its-kind work, we also show the possibility of calculating the response of the nucleus using newly developed quantum algorithms and give an alternate method to validate the quantum algorithms by comparing them with the experimental data.

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References

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